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Multi-Stage Explosive-Magnetic Amplifier (FREDA)

Final Report

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ABSTRACT

FREDA is a device for amplifying magnetic flux. A small value of flux is inserted at one end of an array of copper strips and high explosive sheets. When the explosive is detonated at the input end, the field is pushed along the apparatus, and the energy fed into it from the explosive is used to increase the magnetic flux. For most explosive-to-electrical converters it is thought that a flux amplifying device will have decisive advantages over the more common flux compression devices.

A satisfactory low power FREDA stage has been designed. The length is four inches, the gain 1.4. Twenty-five stages of this type have been fired without failure. Currents around 10,000 amperes and fields around 100,000 maxwells have been obtained. The next step is the construction of FREDA chains long enough to run the field up to a value at which the field pressure approaches the explosive detonation pressure, and the design of high efficiency high power stages.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Ben F. Hardaway

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Colonel, USAF
Chief, Weapons Division

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I. INTRODUCTION

The problem of obtaining high electrical energy (megajoules) from an economical device in times which are short (on the order of milliseconds) is one to which much technical effort has been applied. There are many uses for which such a device could be employed such as magneto hydrodynamic studies, large power electromagnetic radiators, etc., provided the energy could be delivered in a usable form. Chemical explosives are inexpensive and release the amount of energy here mentioned in times which are very short but it is difficult to convert the energy to a form which is usable in the devices mentioned above. Considerable effort has been expended in the past few years in an effort to convert chemical energy to electrical energy. These efforts have been partially successful and some experimental devices have been developed which are reported in the open literature.[*1,2]

Most of the methods which have come to the attention of Utah Research and Development Company scientists involve using the explosive to increase the magnetic field trapped between conductors by

* Superscripts refer to footnotes

1. Linhart, J. G., Knoepfel, H. and Gourlan, C., Conference on Plasma Physics and Controlled Nuclear Fusion Research, Salzburg, Sept. 1961.
2. Fowler, Garn and Card, "Production of Very High Magnetic Fields by Implosion," J. Appl Phys 31, 588 (1960).

shorting out the conductors with explosive energy. These devices rely upon a simple volumetric compression ratio to gain an increase in the field intensity. The method for accomplishing this is discussed under the theory section of the proposal. Staff scientists at Utah Research and Development Company have recently developed a method for increasing the field intensity from a simple arithmetical gain due to volume compression to a geometrical progression. This is accomplished by increasing the effective flux between the conductors. The method of accomplishing this is discussed on the following pages.

A. SINGLE-STAGE EXPLOSIVE-MAGNETIC AMPLIFIER

The stored energy in explosives can be converted into electrical energy simply by compression of a magnetic field. Consider a copper cylinder flattened to an oval loop with parallel sides as shown in Figure 1.

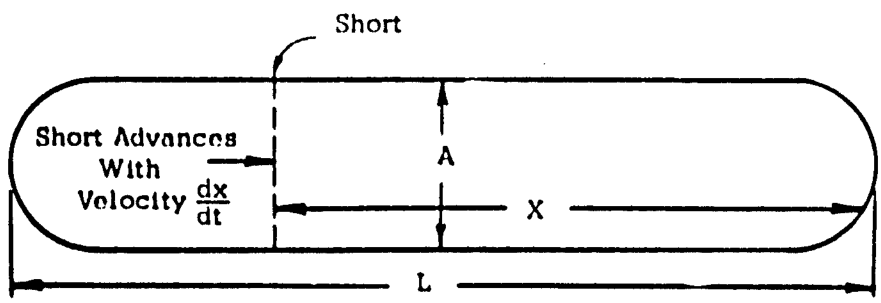


FIGURE 1. SINGLE-STAGE EXPLOSIVE-MAGNETIC AMPLIFIER

The width of the copper sheets perpendicular to the plane of the paper is large compared to the spacing A. If a current is allowed to flow in the walls of the loop and a short circuit advances from one end of the loop to the other with a velocity $\frac{dx}{dt}$, the induced voltage across this short will be,

$$E = AB\frac{dx}{dt} \tag{1}$$

where A = the distance between the plates,

B = the field strength,

x = the distance the short has traveled,

t = time.

The induced voltage across the short will be opposed by a voltage due to the increase in flux density in the remainder of the loop. Neglecting edge and end effects and loop resistance,

$$E = (x)\ (A)\frac{dB}{dt} = AB\frac{dx}{dt} \tag{2}$$

Solving this differential equation,

$$B = \frac{B_o L}{X} \tag{3}$$

Showing that B is inversely proportional to the amount of the loop which has not been shorted out.

Since the field strength, B, is proportional to the current flowing in the conducting loop which is confining this field, as the volume contained in the loop is decreased by mechanically shorting the loop, the current flowing in the loop is increased by the same ratio. The increase in energy represented by this increase in the current is supplied by the force which is causing the short.

In order for the above conditions to operate satisfactorily the collapse of the cylinder with its attendant shorting must take place rapidly so that the material of which the cylinder is constructed acts as a perfect conductor.

Some difficulty arises in meeting this condition at high gain. In the present experimental work some units of the Figure 1 configuration were operated. In shot 1 H-5 the copper sheets were 0.020 inch thick, 1/2" wide, and spaced 1/4" apart. As the Length L is increased, it is evident that the I^2R loss, or rate of flux leakage through the walls increases. For some large volume of L the loss must equal the energy fed in from the explosive. This breakeven length was, in fact, found to be 6.5 inches for shot 1 H-5. In the FREDA unit, to be described, this difficulty in designing long high gain units does not appear.

B. MULTI-STAGE EXPLOSIVE-MAGNETIC AMPLIFIER (FREDA)

A device which amplifies flux must have a fairly complex

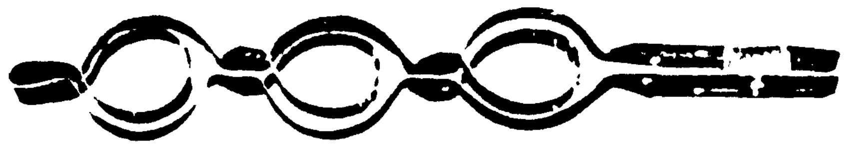
design because Faraday's Law states that the total flux linking a perfect conductor cannot change. This says that the total number of flux lines within a current-carrying loop which is a perfect conductor cannot be increased but it does not preclude that the flux lines in such a loop cannot be bent, twisted, and folded so that they pass through the volume within the loop several times and thus act as though more flux lines had been introduced. To accomplish this, an amplifier must be constructed with paths through which a given flux line can pass back and forth in such a way that it passes through the volume of interest several times instead of once. With this technique, Faraday's Law is not violated because the total flux linkage in the complete amplifier does not change, no matter how many times the paths of a given flux line within the amplifier is twisted and led back through a given volume within the amplifier.

The energy associated with a flux line is large in the region of high flux density so that the unused magnetic field energy stored in the large holes and the space surrounding a FREDA amplifier can be made small compared to that in the working volume between the closely spaced parallel plates. It is irrelevant whether we have many flux lines passing through the working volume or whether the same flux line passes through it many times. Flux lines are in fact imaginary and the difference between

many flux lines and many segments of the same line is largely a matter of what convention one chooses to adopt in counting them.

The FREDA amplifier satisfies these criteria and provides for an unlimited amplification factor within the limits set up by the magnitude of the force applied by the explosive charge used to collapse the amplifier.

A three-stage FREDA amplifier is shown in Figure 2. It can be seen that it starts on the left side of the photograph in the same way as the single-stage magnetic field amplifier described in Figure 1, but each parallel lead branches into two pairs of leads. Each branch is from the viewpoint of the other a shunt inductance and the magnetic flux in each branch when the short has advanced to a fork from the preceding one will be equal to the total initial flux. The branches can then be led around to join in such a way that these fluxes add. Therefore, the flux is doubled at each stage except for various small losses. Twenty ideal stages will give a gain of one million in field intensity.



Input ←——→ Output

FIGURE 2. FREDA UNIT FOR DEMONSTRATION PURPOSES, SHOWING THE ELECTRICAL CONNECTIONS

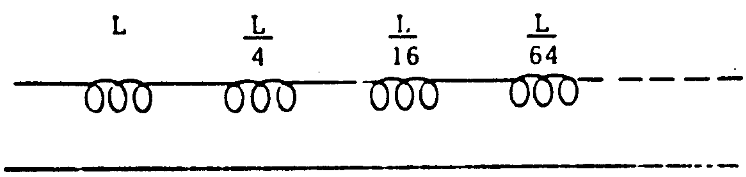
II. THEORETICAL ANALYSIS OF FREDA AMPLIFIER

A. THE RUBBER BAND THEORY

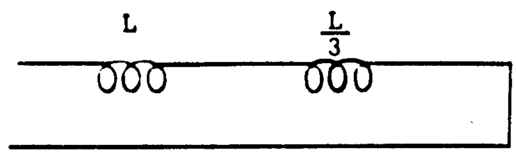
Magnetic flux lines linking a perfect conductor are endless loops which are incapable of moving through the conductor but free to move in air spaces. They are indestructible. In the ideal case the behavior of flux lines can be approximated very well by that of a rubber band. Pushing the rubber band through the device gives some insight into the way magnetic flux lines behave when forced through it by an advancing short circuit driven by explosives.

B. CIRCUIT DIAGRAM THEORY*

It can be seen from symmetry that a current flowing through a FREDA unit divides in half every time it goes through a node. The stored energy in successive stages drops by a factor of 4, so one may represent the system with a circuit of series inductances as,



or lumping all inductors after the first,



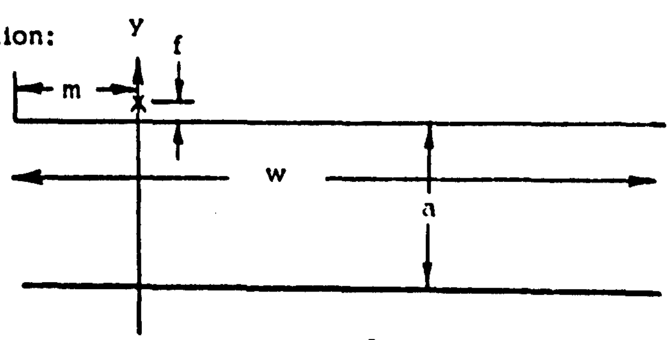
* Due to Drs. Kolbo and Lupton, U. S. Naval Research Laboratory

If a short circuit is run through the first stage, the inductance of the whole system drops from 4/3L to 1/3L, and the current increases correspondingly by a factor of 4. Then the current divides in half at the node, and the final result assuming perfect conductors is an increase in the current by a factor of two per stage, in agreement with the rubber band analysis.

C. DETAIL THEORY

Due to the peculiar shape of the FREDA device, a detailed analysis of its operation would be a rather difficult computer problem. One would have to calculate the field and consequent current distribution and losses at a position of the short circuit. Then the short circuit would be allowed to advance one step, with an energy input obtainable from the field distribution, and a new set of fields, currents and losses computed. No calculation approaching this complexity has been carried out, but some simple field theory calculations have been found relevant.

Parts of the flux amplification apparatus resemble wide, flat, parallel, current-carrying strips. It is necessary to investigate some features of the magnetic field around them. Consider the following idealization:



A uniformly distributed current, I, flows into the top strip and out along the bottom strip. If the conductors are wide compared to the separation between them, the field intensity between them is $\frac{\mu I}{w}$ and the field elsewhere is negligible. For a separation of one centimeter and a width of two centimeters, as recently used experimentally, this approximation is insufficient. The outside field is not negligible and is calculated below for a point at a distance, m, from one edge of the strip and a short distance, f, outside it.

The field at a distance, R, from a long, straight current is,

$$B = \mu I/2\pi R \tag{4}$$

Due to the top current sheet,

$$dB = \frac{\mu\, dI}{2\pi R} = \frac{\mu I/w \quad dx}{2\pi\sqrt{x^2+f^2}} \tag{5}$$

The x component of the field is the most important, and is

$$dB_x = \frac{\mu If \quad dx}{2\pi w(x^2+f^2)}$$

$$B_x = \int_{-m}^{w-m} \frac{\mu If}{2\pi w}\,\frac{dx}{x^2+f^2} \tag{6}$$

$$= \frac{\mu I}{2\pi w}\left[\arc\tan\frac{(w-m)}{f} - \arc\tan\left(\frac{m}{f}\right)\right]$$

Since f is small, the arc tangents are nearly 90°, and

$$B_x = \frac{\mu I}{2w} \tag{7}$$

The field contributed by the bottom strip may be found in the same way, and the total field just outside the strip is found to be,

$$B_x = -\frac{\mu I}{2\pi w}\left(\text{arc tan}\frac{a}{w-m} + \text{arc tan}\frac{a}{m}\right) \tag{8}$$

If w = 2a, then for any value of m along the current carrying strip,

$$B_x \simeq 1/4 \frac{\mu I}{w} \quad . \tag{9}$$

Between the strips, the field is nearly uniform and equal to,

$$B_x = 3/4 \frac{\mu I}{w} \tag{10}$$

The field in the center of the apparatus and its inductance are found to be 3/4 of the value computed on the wide strip approximation. The wide strip approximation may also be stated as the approximation neglecting the fields outside the current carrying strips.

$$\begin{aligned} L &= 3/8\mu \text{ webers/amp-meter} \\ &= 4.7 \times 10^{-7} \text{ henries/meter} \end{aligned} \tag{11}$$

The power fed into a section of this line by collapsing it is

$$P_1 = I^2 \, dL/dt \tag{12}$$

For a detonation velocity of 7000 m/sec,

$$P_i = 3.3 \times 10^{-3} \ I^2 \tag{13}$$

It is interesting to compare this to power consumed in the resistance of the strips. If they are 1/2 mm thick, (0.020 inches), the resistance is 3.2×10^{-3} ohms per meter,

$$P_R = I^2R = 3.2 \times 10^{-3} \ I^2 \tag{14}$$

From this calculation, it appears that the simple flux compressor would maintain a constant field, resistance losses balancing power input from flux compression if it were about one meter long. As the explosive collapse proceeds making it shorter, the field should increase. It is found experimentally that the breakeven length for leads of this size is 43 cm. Losses in the copper strips under explosive attack are thus substantially larger than the ideal DC resistance losses, but not overwhelmingly so.

Losses in a FREDA device may be classified as resistive and inductive. In other terms, flux lines may escape by leaking through the walls (resistive or I^2R loss) or the closing conductors may catch a group of them and leave them behind in a pocket. Flux trapping at the nodes is in fact serious in FREDA.

Resistance losses, including contact resistance, can always be made small by scaling up the apparatus. Inductance (flux trapping) losses are independent of scale and must be controlled by regulating the collapse process so that the pockets left between FREDA plates are sufficiently small. Putting explosive on both sides, so that the plates meet at an angle near 30° as they are driven together, helps to greatly reduce inductive losses.

III. THE GEOMETRY OF FREDA

All FREDA units tested to date have been topologically identical. The following are configurations which have been considered during this study.

The cylindrical configuration, Figure 3, is attractive because the explosive loaded on the outside always compresses the copper strip as it is driven down and shorted against the inner strip. In other configurations copper is stretched by the explosive, and tends to break in tension and lose continuity. This leads to loss of the field and complete failure of the unit. Cylindrical devices were in fact found to have excellent reliability, but their gain was poor. It seems that magnetic flux was somehow trapped at the nodes. This loss was improved in linear types by putting explosive on both sides, but the cylindrical type is not well adapted to this.

The most primitive FREDA unit is the linear skewed type, Figure 4. This works with explosive on both sides, with a gain of about 1.3 per stage, each stage being four inches long. It is hard to manufacture to satisfactory tolerance because of the skew. Its reliability is low.

The present series of investigations terminated in the P design of the linear barred type, Figure 5 and 6.

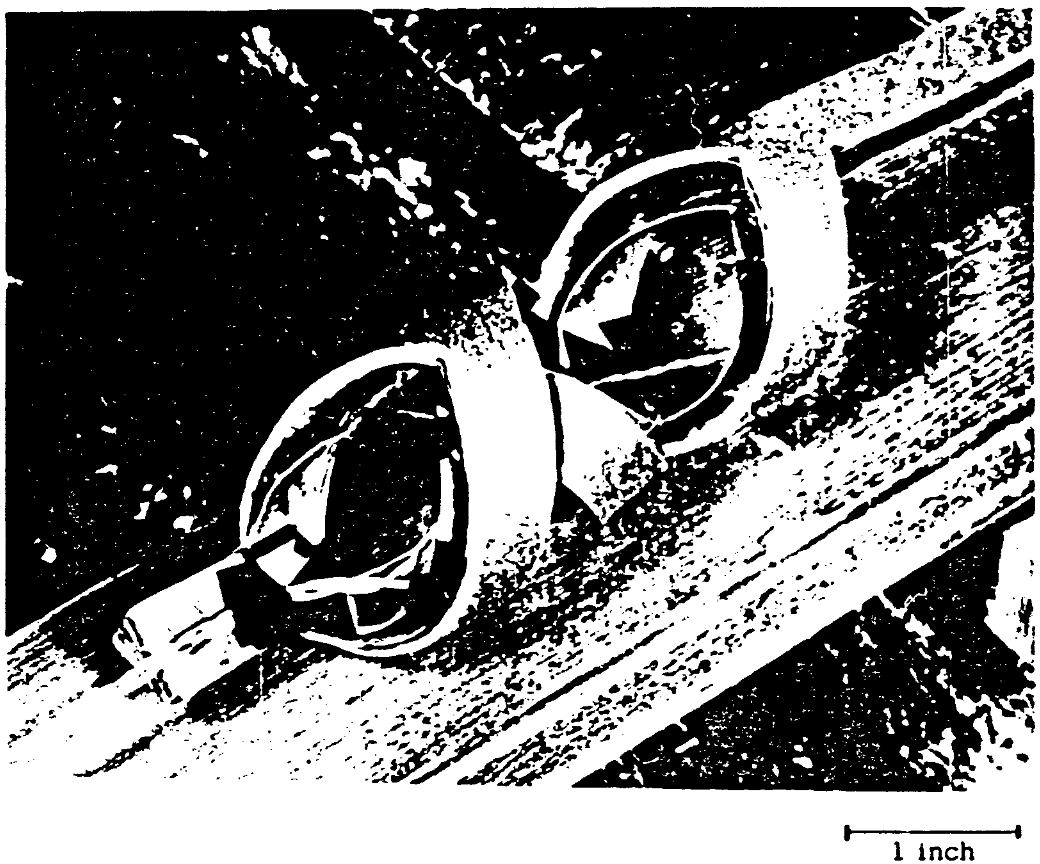


FIGURE 3. CYLINDRICAL FREDA UNIT

FIGURE 4. LINEAR SKEWED FREDA UNIT

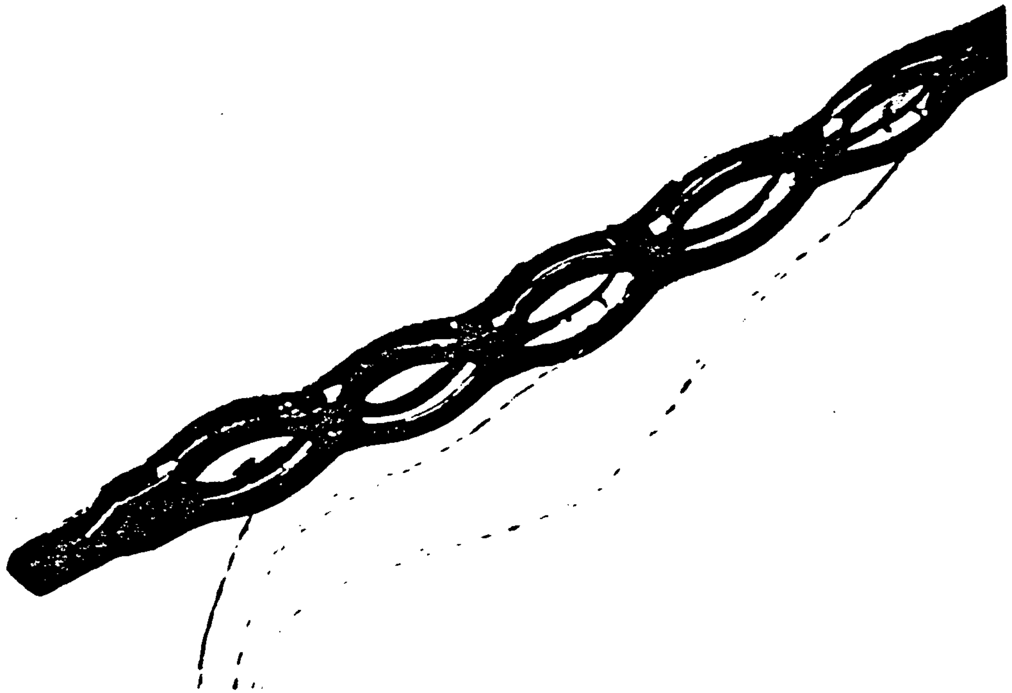


FIGURE 5. LINEAR BARRED FREDA UNIT

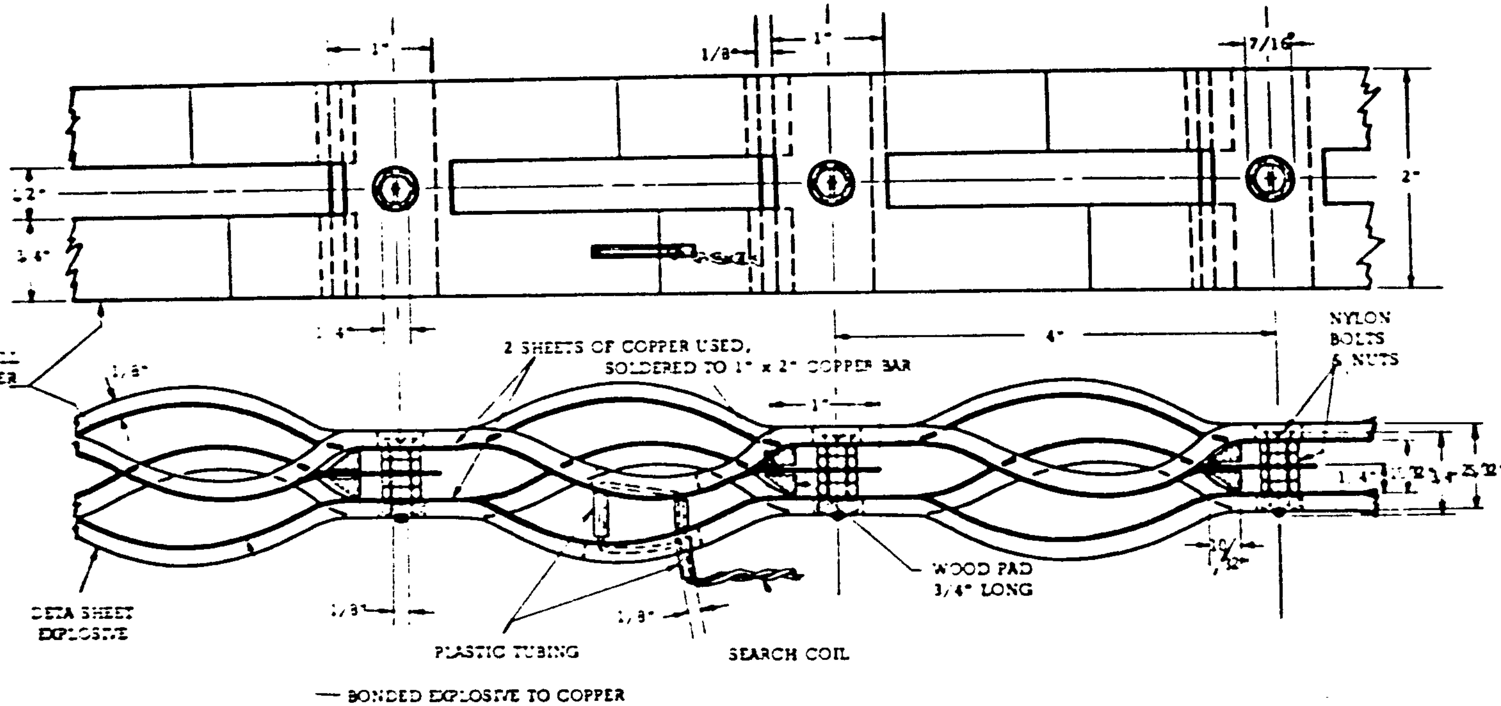


FIGURE 6. FREDA UNIT LINEAR BARRED TYPE 5P

Its gain and reliability were investigated by firing 5 identical units, each of which contained five stages. None of these 25 stages failed catastrophically. The average gain for all stages observed was 1.4. The gain and reliability of the P design were found to be quite adequate for constructing the low power stages of a full scale FREDA device. Linear barred chains could be easily paralleled if necessary. For this type of use it is necessary that the probability of failure of the FREDA unit be made very low.

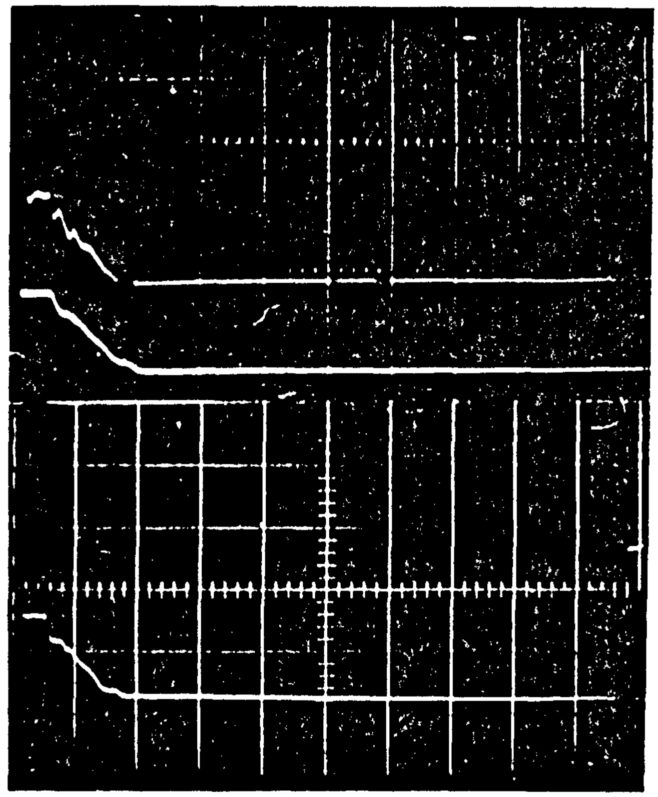
Linear barred units can readily be constructed in large sizes. FREDA 4 Q-7 was made very large to obtain gain with explosive on one side only, with stages a foot long. It worked with a gain of 1.35 per stage.

IV. INSTRUMENTATION

The functioning of FREDA units has been observed with search coils mounted in the middle of the stages. (See Figure 6.) The output voltage is equal to the rate of change of the flux linking the search coil. Since the flux itself, or the current associated with it, is more interesting, it is convenient to integrate the signal from the search coil before displaying it. This signal is therefore passed through a 100 ohm, 10 microfarad integrator and then to the oscilloscopes. The low resistance and large capacitance of the integrator are required because explosives generate electrostatic voltages which would complicate the signals observed with a higher impedance integrator.

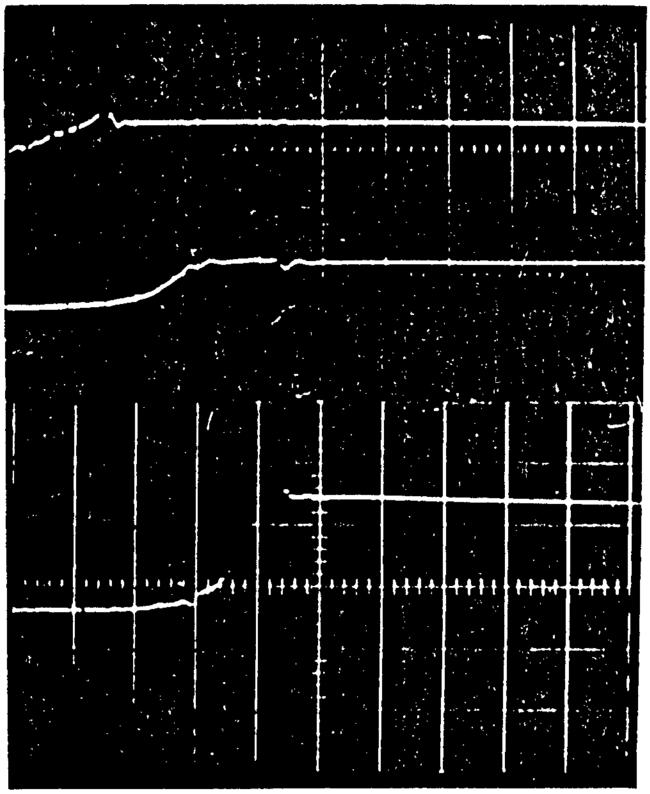
A calibration check on the integrators, lines, and oscilloscopes is required. It is convenient to attach all channels to one search coil in a flux compressor. Nearly identical outputs are observed, as in Figure 7, and on the final data small corrections can be made for the observed differences in the sensitivity of the channels.

In Figure 8 deflections proportional to the currents in the FREDA stages appear on the traces. Note that the current comes on immediately in the first stage. The current in the last stage does not become appreciable until the middle stage is destroyed, and the explosive driven short circuit is two stages away.



Time 20 Microseconds/cm

FIGURE 7. CALIBRATION PULSES ON FREDA INSTRUMENTATION, SHOT 5P-1 ACCIDENTALLY INVERTED



Time 20 Microseconds/cm

FIGURE 8. DATA ON FREDA SHOT 5P-1, FIVE STAGE LINEAR BARRED TYPE, SEARCH COILS IN EVERY OTHER STAGE

The distinctive characteristic of the FREDA device shows well on these traces. The volume of the field does not change as it operates. Only its intensity is affected. The condenser bank fills only the first stage or two with magnetic field, and the fields, currents, and losses continue to be confined to one or two stages.

The FREDA unit has nothing resembling the breakeven length discussed under flux compressors. An infinite chain of FREDA stages has only 4/3 the resistance, inductance, and losses of one stage. The experimental units were terminated in 4/3 of the impedance of one stage, so the gain reported is the gain the stage would show if connected into a full scale FREDA unit, with a long chain of stages running in both directions from the stage being considered.

V. RESULTS *

Theoretical analysis and results from flux compressors show that resistance losses are fairly small, on the order of 25% of the input to the magnetic field, for FREDA stages 4 inches, 10 cm, long and made of copper strips 3/4" wide and spaced 3/8" apart. Failure to obtain gain in such units with explosive on one side only was apparently due to flux trapping at the nodes.

One piece of evidence was obtained by comparing 2 L-4 and 2 L-5. In this pair of skewed linear units, an improvement factor of two in gain was obtained by placing plates closer together where the explosive, on one side only, could reach them less effectively. If the plate spacing were regulated with sufficient exactness, the gain of such units should go up to 1.3 or 1.4 equaling that of units with explosive on both sides. We failed in practice to achieve reliably a gain above unity, in normal size units.

Further experimental studies of scaling were made with cylindrical FREDA units. Units 3 M-1, 2, 3, 4 gave a gain very near unity. Scaling up throughout by a factor of two, units 3 Q-2, 4, gave no improvement.

One enormous linear barred unit, 4 Q-7, was built partly to test scaling theory, showing that high gain can always be obtained by brute force, and partly because such units may be useful for handling

* Raw data are reported in Appendix A.

high power. It had explosive on one side only, but the stages were made a foot long so the nodes make up a small part of the machine and flux trapped in them is made a small fraction of the total. This unit worked properly with a gain of 1.35 per stage.

This gives further confidence in the prediction that the very general property of electrical machines, the increase in efficiency and decrease in resistance effects with increasing scale, applies to FREDA. Extrapolation indicates that a full scale FREDA output stage, with a volume between plates of perhaps a cubic meter and an output around 500 mega-joules, would have negligible resistance losses.

We have had some preference for FREDA units with explosive on one side only on the grounds that the explosive on the two sides may get out of step, producing erratic results. No trouble has appeared in practice, so it is concluded the two layers of explosive interact sufficiently to keep the detonation fronts in step. Therefore, the 5P unit, with explosive on both sides and a gain of 1.4 per stage, was selected as a standard low power stage. Twenty-five such stages in five groups were fired in a reliability test. All worked.

VI. CONCLUSION

A large part of the present program was spent in acquiring such modest but vital bits of information as the following:

1. When 0.020" copper sheet is driven down against wood or rubber, it remains continuous after first contact while the detonation front advances about two inches. Then it breaks.
2. If an airspace of 3 mm appears between detasheet and copper strip, the strip is likely to break at that point before it travels a centimeter.
3. A sheet of copper 0.020" thick bonded to 1/8" detasheet is driven across a one cm gap by the explosion in 6 microseconds, with an average velocity near 1.5 km/sec. The explosive detonation velocity is 7.0 km/sec.

We now have the art of manipulating sheet copper with explosive under good control. We have in the 5P FREDA unit an adequate low power stage. The saturation current obtainable from these small units is not known, but it can hardly be over a million amperes. Since cheap condenser banks can deliver up to 10^4 amperes, no more than 15 5P units

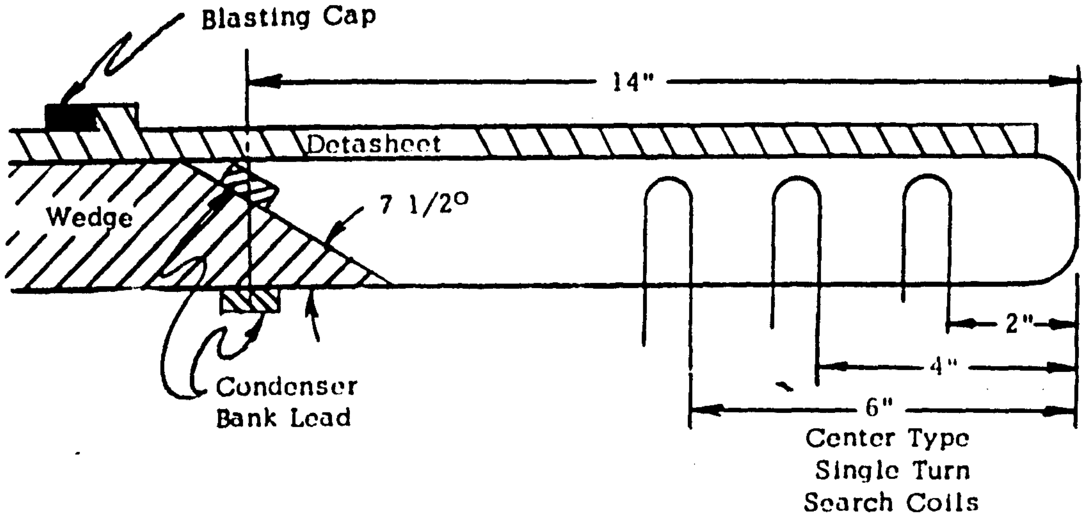
in series, with a gain of 100, are ever likely to be used. Such a fifteen stage unit would be five feet long, weighing ten pounds or so. Its condenser bank, with leads, might weigh as much again. The material cost of a SP stage is about $1, and the labor cost estimated at $10.

The next step is the design of high power FREDA stages.

APPENDIX A

COMPILED DATA FROM FREDA TEST FIRINGS

A. Simple Flux Compressors



H Series

Before the explosion reaches the first search coil, all should indicate the same current passing from the condenser bank around the loop of copper strips. Then the search coil outputs peak in sequence. If the copper strip breaks, the current indicated by all search coils should drop quickly to zero. Results were as follows:

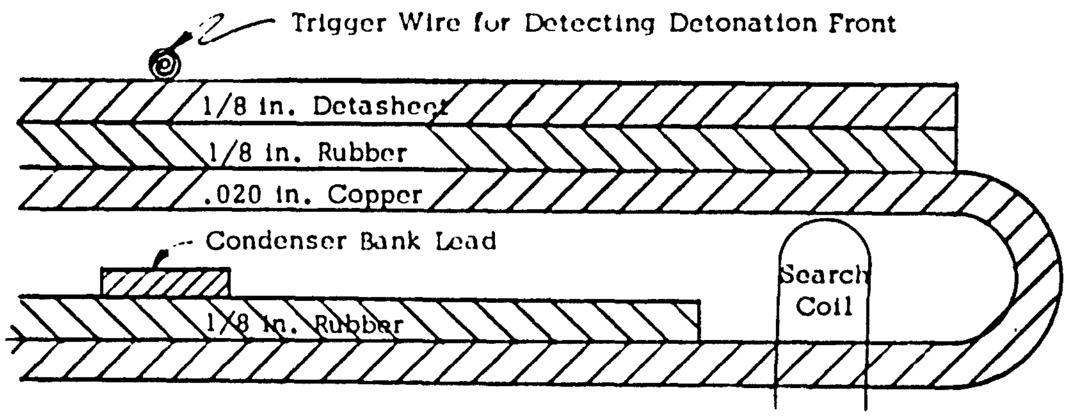
1 H-1	Strip broke at 25 microseconds, at about the time the upper strip hit the tip of the wooden wedge.
1 H-2	Interpretation of traces not clear.
1 H-3	Apparatus functioned correctly.

1 H-4 Apparatus functioned correctly.

1 H-5 Copper strip reduced to 1/2" wide with 1/4" spacing. Apparatus functioned correctly.

1 H-6 Same as H-5. Strip broke early, at about the time the upper strip hit the upper condenser bank lead.

A test was conducted to show whether a rubber pad placed between the copper strip and the explosive would protect the metal and reduce strip breakage. The apparatus is shown schematically below:



I Series Apparatus for Measuring Collapse Velocity

The results were as follows:

1 I-2 With rubber pad between explosive and metal. The switch closed 9.5 microseconds after the detonation wave passed, indicating a collapse velocity of one kilometer per second. The strip broke, returning the field in the search coil to zero, ten

microseconds later. The detonation velocity of detasheet is about 7 km/sec, so the collapse advanced 7 cm before the strip broke.

1 I-3 Without rubber pad between explosive and copper strip.

In this shot the copper strip was driven across the one centimeter gap to switch on the capacitor bank in 6 microseconds, and the strip broke 8 microseconds later.

From this brief experimental program, it has been concluded that a rubber pad is not very helpful in protecting the copper strips. Further, it was decided that the 7 1/2 degree wooden wedge used in the switch was too long and a 15 degree wedge was adopted for further experiments.

It is possible to evaluate certain losses from shots H-3, H-4, and H-5. In a very long flux compressor, the I^2R loss in its resistance will exceed the power input due to compression of the field by the explosive-driven short circuit shortening the loop. A search coil at the closed end will then show an increase of field as the condenser is switched onto the loop. As the collapse continues, the condenser will be shorted. Current and field will then decrease until the loop is shortened to the break-even point where power input equals the I^2R loss. Beyond this point

current and field detected by the pickup coil increase. The observed length of the loop at the break-even point is 6.5 inches for loops 1/2" wide, 1/4" spacing and 17" for loops 3/4" wide with 3/8" spacing. Both types were made of cold rolled copper 0.020 inches thick. The theoretical length of the loops at the break-even point has been calculated, assuming that the only losses were DC resistance losses. The calculated lengths were 25" and 38".

Two simple compression units with 3/4" width and 3/8" spacing were constructed with two turn pickup coils on the edges. Both broke at about the time the explosion reached the first pickup coil. Probably failure occurred because insufficient care was taken to lay the explosive flat and in contact with the copper sheets near the coils.

1 Q-1 — Double scale type, copper strip 0.040 inch thick next to explosive, 0.060 inch on base. Strip width 1 1/2", spacing 3/4". Functioned correctly.

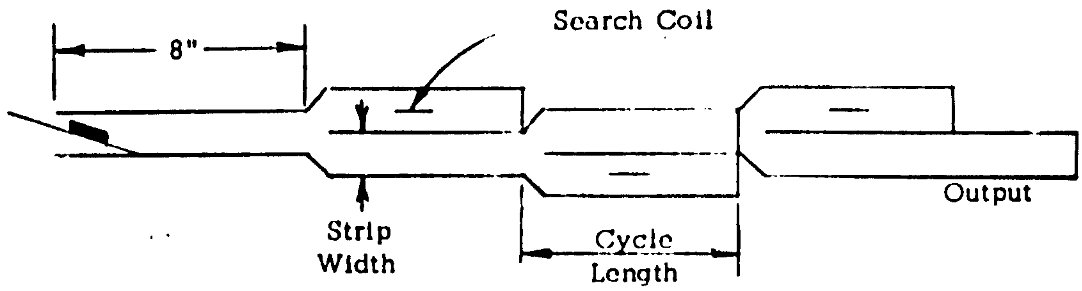
1 Q-10 — Flux compressor used as system check. All the lines to the integrators were connected to a single search coil. The indicated current was the same in time and amplitude on all traces, as expected.

B. Multistage Coils, Linear Skewed Type (See Figure 4.)

<u>Multistage Coils, Series 2L</u>

The Series L loops are three-stage FREDA units. Center-type single-turn pickup coils were placed in the bottom half of each loop.

The cycle length is illustrated below on one of the two copper strips which assemble to form a FREDA unit. The sheet copper was 0.020" thick next to the explosive and 0.030" thick on the base. Explosive was placed on one side only.



2 L-1	3/4" strip width, 3/8" spacing	
2 L-2	3" cycle length	
	Both of these coils failed in first loop.	
2 L-3	3/4" strip width, 1/4" spacing	
	3" cycle length	
	Significance of search coil outputs not clear.	
2 L-4	3/4" strip width, 1/4" spacing	
	3" cycle length	
	Peak currents in copper strips:	
	First coil	5000 amps
	Second coil	2500 amps
	Third coil	Broke

Gain definitely below unity.

2 L-5	Loops slightly asymmetrical to facilitate uniform collapse under explosive attack.	
	3" cycle length	
	Peak currents:	
	First coil	7000 amps
	Second coil	4800 amps
	Third coil	5500 amps
2 L-6	Loops slightly asymmetrical to facilitate uniform collapse under explosive attack.	
	3" cycle length	
	Peak currents:	
	First coil	5000 amps
	Second coil	6000 amps
	Third coil	Broke
2 L-7	3/4" strip width, 1/4" spacing	
	4" cycle length, slightly asymmetrical	
	Peak currents:	
	First coil	6000 amps
	Second coil	3500 amps
	Third coil	No data
2 L-8	3/4" strip width, 1/4" spacing	
	4" strip length, slightly asymmetrical	

Peak currents:

First coil	5000 amps
Second coil	4500 amps
Third coil	5000 amps

2 L-9 3/4" strip width, 1/4" spacing

4" strip length, slightly asymmetrical

Peak currents:

First coil)	Search coil outputs peculiar
Second coil)	
Third coil	6000 amps

2 L-10 3/4" strip width, 1/4" spacing

4" strip length, slightly asymmetrical

Peak currents:

First coil	3500 amps
Second coil	No Data
Third coil	3500 amps

2 L-12 3/4" strip width, 3/8" spacing

4" strip length, slightly asymmetrical

Peak currents:

First coil	3500 amps
Second coil	No Data
Third coil	3500 amps

Strip broke about the time the explosion reached

the first loop.

2 Q-3 8" cycle length, 1 1/2" wide strips 0.040 and 0.060 inch thickness explosive on one side only.

Peak currents:

First coil	2000 amps
Second coil	3000 amps
Fourth coil	Zero

Doubler failed in third loop. Data from first loop doubtful.

2 Q-5 4" cycle length 3/4" wide strips 0.020 inch thick 1/4" spacing explosive on both sides

Peak currents:

Second coil	8200 amps
Third coil	12000 amps
Fourth coil	Over 15,000 amps (off scale)

2 Q-11 4" cycle length, 3/4" wide strip, 1/4" spacing explosive on both sides

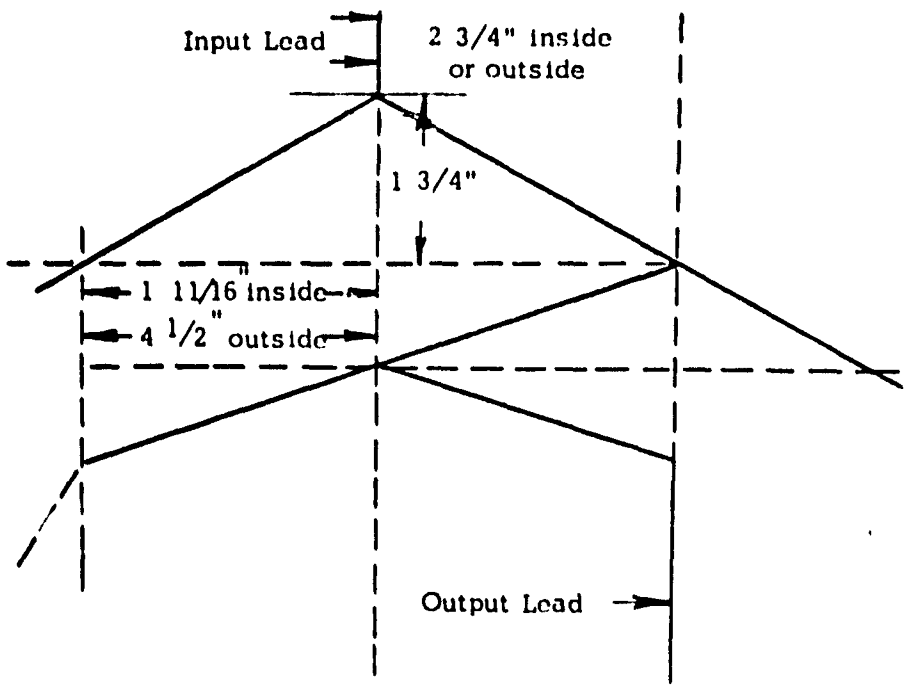
Peak currents:

First coil	1400 amps
Third coil	2100 amps
Fourth coil	2800 amps

Gain 2.0 in three stages, 1.25 per stage

C. Multi-stage Coils, Cylindrical Type (See Figure 3.)

These coils are wound from a pair of branching copper strips, one strip being bent into a small inside cylinder and the other one forming a larger outside cylinder. In the M series the center line of the copper strip formed the following pattern:



The outside lead, wound on a cylinder 2 1/4" in diameter, was of copper 0.020 inch thick. The inside lead, wound on a cylinder 1 1/2" in diameter, was 0.030 inch copper. The leads were 3/4" wide and spaced 3/8" apart.

3 M-1 Search coils installed around waste flux passing through inner cylinder. Interpretation of data not clear.

3 M-2 Search coils in normal position between leads.

Peak currents:

First coil	6500 amps
*Second coil	4000 amps
Third coil	6500 amps

3 M-3 Search coils in normal position between leads.

Peak currents:

First coil	5500 amps
*Second coil	3500 amps
Third coil	4700 amps

*Second search coil placed on wrong side of loop. Reading not fully comparable to first and third.

3 M-4 Six-stage coil with search coils in the center four to avoid end effects.

Peak currents:

Second coil	4000 amps
Third coil	2500 amps
Fourth coil	3000 amps
Fifth coil	3000 amps

3 Q-2	Double scale unit over M type copper strips 0.040 and 0.060 inch thickness, 1 1/2" wide, 3/4" apart.	

Peak currents:

First coil	4000 amps
Second coil	2500 amps
Third coil	2800 amps

3 Q-4 Double scale unit over M type copper strips 0.040 and 0.060 inch thickness, 1 1/2" wide, 3/4" apart.

Peak currents:

First coil	4500 amps
Second coil	4800 amps
Third coil	3800 amps

3 Q-7 Copper strips 0.020 and 0.030 inch thick, 3/4" wide, 3/8" spacing, and wound with the inner cylinder 3 1/2" in diameter.

Peak currents:

First coil	7000 amps
Third coil	4000 amps
Fourth coil	7000 amps

D. Multi-stage Coils Linear Barred Type. (See Figure 6.)

4 Q-6 Four inch cycle length. Copper strips 3/4" wide, 0.020 and 0.030 inch thick. Explosive on one side only. No wood pads.

Peak currents:

First coil	5000 amps
Third coil	4800 amps
Fourth coil	5100 amps

4 Q-7 One foot cycle length. Copper strips 1 1/2" wide, 0.040 and 0.060 inch thick. Explosive on one side. With wood pads.

Peak currents:

First coil	1700 amps
Second coil	2400 amps
Fourth coil	4200 amps

Gain 2.5 in three stages, 1.35 per stage.

4 Q-12 Four inch cycle length. Copper strips 3/4" wide, 0.020 inch thick, space 1/4" apart. Explosive on both sides. No wood pads.

Peak currents:

First coil	1700 amps
Third coil	1400 amps

4 Q-13 Four inch cycle length. Copper strips 3/4" wide, 0.030 inch thick, spaced about 1/4" apart. No wood pads.

Peak currents:

First coil	2100 amps

Third coil	1900 amps
Fifth coil	2100 amps

4 Q-14 Four inch cycle length copper strips 3/4" wide, 0.020 inch thick, spaced about 3/8" apart. Explosive on both sides. No wood pads.

Peak currents:

First coil	1300 amps
Third coil	1500 amps
Fifth coil	2200 amps

Gain 1.7 total, 1.14 per stage.

E. Series P

Linear barred doubler, see Figures 5 and 6 . Four inch cycle length, copper strips 3/4" wide by 0.020 inch thick, held apart to about 3/8" spacing by nylon bolts.

Explosive 1/8" thick glued on both sides, with wooden pads. Center-type single turn search coils installed in the middle of every other stage. Calibration measurements were made on scopes and integrators, and relative peak current measurements corrected.

This unit has been selected for service in generating large currents for use in testing high power units in the future. Five identical units were fired as a final check on its reliability.

5P SERIES

Stage	Time of Current Peak, Microseconds	Trace Deflection cm	Peak Current Amperes	Gain Per Stage
Test Unit 5P-1				
1	28	0.4	2000	1.4
3	57	0.7	4000	1.54
5	84	1.9	9500	
1-5				1.47
Test Unit 5P-2				
3	62	0.7	4000	1.4
5	96	1.6	8000	
Test Unit 5P-3				
1	36	0.38	1900	1.3
3	64	0.65	3000	1.47
5	96	1.3	6500	
1-5				1.36
Test Unit 5P-4				
3	64	0.8	3700	1.4
5	92	1.45	7200	
Test Unit 5P-5				
1	34	0.25	1300	1.47
3	62	0.6	2800	1.27
5	90	0.9	4500	
1-5				1.36

Overall average gain of P - Series 1.40

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